

AMMONIA EMISSIONS FROM TWELVE U.S. BROILER CHICKEN HOUSES

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ABSTRACT. Twelve commercial broiler houses in the U.S. were each monitored for at least thirteen 48 h periods over the course of one year to obtain ammonia emission data. Paired repetition of houses on four farms represents current construction with variety in litter management (built-up or new litter each flock) and climate conditions (cold or mixed-humid). Ammonia concentration was determined using portable electrochemical sensors incorporating a fresh air purge cycle. Ventilation rate was determined via in-situ measurement of fan capacity, fan on-off times, and house static pressure difference. There were seasonal trends in exhaust ammonia concentration (highest in cold weather) and ventilation rates (highest in warm weather) but not for emission rate. Flocks with at least three monitoring periods (13 of 22 flocks) demonstrated similar emission rates at a given bird age among the four study farms and across the seasons. An analysis of emissions from all houses on the three farms using built-up litter resulted in predicted regression slopes of 0.028, 0.034, and 0.038 g NH₃ bird⁻¹ d⁻¹ per day of age; the fourth farm, managed with new litter, had the lowest emission rate at 0.024 g NH₃ bird⁻¹ d⁻¹. The intercept of these composite relationships was influenced by litter conditions, with flocks on new litter having essentially no emissions for about six days while built-up litter flocks had emissions starting at flock placement. Data from all four farms and all flocks provided a regression slope of 0.031 (±0.001 std error) g NH₃ bird⁻¹ d⁻¹ per day of age. Emission rate per animal unit for built-up litter flocks indicated very high emissions for the youngest birds (under 14 days of age), after which time the emissions decreased exponentially and were then relatively steady for the balance of the flock cycle.

Keywords. Ammonia emissions, Broiler houses, Electrochemical sensor, Litter treatment, NH₃ concentration, Poultry, Seasonal variation, Ventilation rate.

Reasonable estimates of ammonia emissions are needed by poultry industry professionals so that they can participate in discussions about their industry's impact on local and regional air quality. There are a limited number of scientific estimates of ammonia emissions from U.S. poultry facilities, despite the interest of agencies and concerned citizen groups in mitigating ammonia emission from livestock facilities (NRC, 2003). A U.S. Environmental Protection Agency (EPA)-funded am-

monia inventory study (Battye et al., 1994) has been widely used in estimating agricultural contributions to U.S. ammonia totals. Although broiler houses may appear to be similar throughout the U.S., there are differences in housing styles, management, equipment selection, bird husbandry, and maintenance that directly impact effectiveness of the environmental control system in the houses, which in turn affects the emission rate.

Emission rate is approximately the product of ammonia concentration and ventilation exhaust airflow rate. While this calculation is simple in concept, in practice, both concentration and ventilation are difficult to measure accurately under commercial poultry house conditions. Mechanically (fan) ventilated facilities should in principle be more easily monitored than naturally ventilated facilities because ventilation rate can be determined from summing the individual fan capacities and run-times. Ammonia monitoring instruments suffer from challenges of high cost for highly accurate models and inconsistent accuracy and reliability for more affordable sensor technologies (Gates et al., 2005a). Emission rate from livestock housing is often expressed in terms of mass of ammonia release per mass of animal housed over a given time period. Broiler chicks, weighing about 40 g each at placement, grow rapidly to market weight (2 to 3 kg) birds. Thus, both number and weight of birds need to be known in determination of the emission rate.

The objective of this study was to document ammonia emission rates from typical commercial broiler houses in the U.S. A primary goal was to collect high-quality, representative emission data from a variety of farms with a cost-effective strategy. This study was part of a larger USDA-funded

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project that documented ammonia emissions and mitigation strategies from ten laying hen houses and twelve broiler houses on commercial farms in three U.S. regions. The companion article on ammonia emissions from laying hen houses in Iowa and Pennsylvania was published earlier (Liang et al., 2005).

METHODS

STUDY HOUSES

Environmental conditions in twelve commercial broiler houses in Kentucky (KY) and Pennsylvania (PA) were monitored, each during at least thirteen 48 h periods over the course of one year. The monitoring periods provided data to determine ammonia emission from the broiler houses during different seasons with birds of various age during at least five flock grow-out cycles. Overall, 400 days of ammonia emission data were collected during the study year. In order to obtain data economically from as many houses as possible over the year, the instrumentation was taken to one set of houses the first week and to another set of houses the second week. The interval between 48 h collection periods was typically three weeks in PA and two weeks in KY. Additional

time was spent in data organization, instrumentation checks, and thorough cleaning for biosecurity. A “day” of data collection started when all the instrumentation was installed in the house and ended 24 h later. Four of the study houses were in PA, representing a “cold” climate, and eight were in KY, representing a “mixed humid” climate. Average 30-year heating degree-days at 18.3 °C base are 3250 and 2625 (5200 and 4200 at 65 °F base) for PA and KY, respectively, based on the nearest available climate data (NCDC, 2000). Farms were selected to represent the variety in current broiler production practices, including those that practiced methods that were presumed to reduce ammonia emissions.

STUDY FARMS

On each study farm, the houses were paired for repetition of conditions: two cold-climate farms were monitored with two houses each; two mixed-humid farms had four houses each. Each farm had a different manager under contract to different companies.

Tables 1 and 2 provide more description about the unique features of the study houses and environmental control systems. All houses in the study had ventilation eave box inlets placed about 3 m apart along both sidewalls. All houses

Table 1. Description of twelve studied broiler houses and flock features, including typical market class of birds housed.

	Dimensions, m (ft)	No of Birds Placed	Placement Density, bird m ⁻² (market class, size, and kg bird ⁻¹)	Construction			
				Date	Walls	Floor	Brooding Chamber
Mixed-humid climate							
KY-A, houses 1-3	12.2 × 152.5 (40 × 500)	25,000	10.75 (49 d, heavy broiler, 2.5)	2000	Insulated stud with 120 cm tall	Packed dirt	50% house
KY-A, house 4	12.2 × 157.4 (40 × 516)	25,000	10.75 (49 d, heavy broiler, 2.5)	1995	single-layer curtain		
KY-B, houses 1-4	12.2 × 152.5 (40 × 500)	20,000	13.44 (60 d, roaster, 3.3)	1997	Insulated stud with 67 cm tall	Packed dirt	50% middle house
		25,000	10.75 (49 d, heavy broiler, 2.5)				
Cold climate							
PA-A, houses 1, 2	14.6 × 152.4 (50 × 500)	32,700	14.7 (42 d, broiler, 2.2)	2001	Insulated stud	Packed shale	40% house
PA-B, houses 2, 3	14.6 × 152.4 (50 × 500)	32,500	14.6 (42 d, broiler, 2.2)	2000	Insulated stud	Concrete	Whole house

Table 2. Description of environmental control features of the twelve studied broiler houses.

	Heaters ^[a]		Ventilation Equipment					
	Brooding Section	Non-Brooding Section	SPC Inlet ^[b]	Fans, 91 cm (36 in.)	Fans, 122 cm (48 in.)	Fans, 127 cm (52 in.)	Controller	Minimum Ventilation
Mixed-humid climate								
KY-A, 4 houses	Pancake style	Unit space	Yes	3	8		Electronic	One 122 cm fan in non-brood section
KY-B, 4 houses	Unit space	None	Yes	6	8		Individual thermostats for each fan/heater	Two 91 cm fans, one in each non- brood section
Cold climate								
PA-A, 2 houses	Pancake style	N/A	Yes	5		10	Electronic	One 91 cm fan
PA-B, 2 houses	Radiant style and unit space	Unit space	Yes	4		10	Electronic, but override thermostats on heaters	One 91 cm fan at non-brood end

^[a] Unit space heaters were non-vented installations.

^[b] SPC inlet = static pressure controlled inlet.

were equipped with tunnel ventilation for use during the warmest weather. Three of the four farms used partial-house brooding; farm PA-A practiced whole-house brooding. All houses had insulated, dropped-ceiling construction.

MANURE HANDLING

New litter is typically provided about once a year in U.S. broiler houses, with caked litter under feeders and drinkers removed after each flock. This reused litter is often referred to as “built-up” litter in the industry and is a combination of the original litter material and accumulated manure; sometimes limited fresh litter is applied (also known as top-dressing) before each new flock is placed. Table 3 includes litter features at the twelve study houses. Some of the houses used a pH-reducing litter treatment to suppress ammonia volatilization. In this article, built-up litter flocks with and without litter treatment are grouped together for comparison to new litter flocks.

All mixed-humid climate houses were managed with built-up litter. The primary difference between the two cold-climate study locations was that the farm PA-A houses had concrete floors and new litter each flock, while farm PA-B had built-up litter on crushed shale floors. Farm PA-B’s second study flock was on new litter after the annual litter cleanout. New litter for both cold-climate farms was kiln-dried wood shavings provided at a depth of 3 cm at farm PA-A and 7 cm at farm PA-B. By the end of five flocks use at farm PA-B, with caked litter removal, litter was about 8 cm deep.

Table 3. Flock placement start dates and the number times litter was used. Study year started in late 2002, with most flocks monitored during 2003. Missing early flock dates were during study start-up when incomplete data prevented full analysis.

Cold Climate					
Farm PA-A			Farm PA-B		
Flock	Start Date	No. of Times Litter Used	Flock	Start Date	No. of Times Litter Used
2	Feb. 3	First	1	Jan. 1	Fifth
3	Apr. 8	First	2	Mar. 6	First
4	June 9	First	3	May 1	Second
5	Aug. 13	First	4	June 18	Third
6	Oct. 14	First	5	Aug. 15	Fourth
			6	Oct. 10 or 14	Fifth

Mixed-Humid Climate					
Farm KY-A			Farm KY-B		
Flock	Start Date	No. of Times Litter Used (House) ^[a]	Flock	Start Date	No. of Times Litter Used
4	Nov. 28	Fourth (1,3) Third (2,4)	2	Nov. 28	Second
5	Jan. 27	Fifth (1,3) Fourth (2,4)	3	Feb. 11	Third
6	Mar. 26	First (1) Sixth (3) Fifth (2,4)	4	Apr. 17	Fourth
7	May 26	First (2,3,4) Second (1)	5	July 1	Fifth
8	July 24	Third (1) Second (2,3,4)	6	Sept. 15	First
9	Sept. 22	Fourth (1) Third (2,3,4)			

^[a] House numbers indicated when not all houses under same conditions.

VENTILATION STRATEGIES

All study houses on all four farms were equipped with two mechanical ventilation systems that shared a common controller (in the case of the eight electronically controlled houses). One ventilation system used sidewall fans and eave inlets for cold and mild weather environmental control, and the second used end-to-end airflow with large inlets and fans for tunnel ventilation. Some of the tunnel fans were also used for mild weather ventilation prior to switching to tunnel mode. Particularly for the first two flocks that were raised during cold weather, the broiler houses were under minimum ventilation to maintain indoor moisture level and air quality. Minimum ventilation settings were also used with young birds. The U.S. broiler industry typically provides minimum ventilation through timer-controlled fan operation. Timer on-time was increased as the birds grew in size to coincide with increased respiratory and excreted moisture levels. The tunnel ventilation strategy was used during the warmer portions of study periods reported here.

FLOCK CHARACTERISTICS

Bird numbers and weights over the entire growth cycle were needed for emission estimates per kg bird weight, per bird, and per 500 kg animal unit (AU) housed. Bird weights for age were obtained from the integrator companies in KY, who had recent field data from electronic or manual weighing of portions of similar flocks. PA bird weights were estimated from field data on birds of the same strains (Cobb-Cobb or Ross Arbor Acre-Cobb) in PA during a previous study (Wheeler et al., 1999), where 1% of the total birds in each of four houses were weighed weekly over a winter flock cycle. The four houses were on three different broiler farms. Birds were caught as a group by surrounding a portion of the flock with a portable pen to capture a representative sample of large, small, fast, and slow individuals. Birds were weighed in-house on a portable electronic scale. All data were combined for analysis of bird weight versus age. Linear regression equations were created to represent the PA houses, with one relationship for young birds and another for older birds, as follows:

For birds less than two weeks old:

$$M = 104.9(\text{age}_W) + 27.8$$

For birds more than two weeks old:

$$M = 440.9(\text{age}_W) - 663.4$$

where M is bird mass in grams, and age_W is bird age in fractions of a week. Polynomial growth curves were developed from growth curve data supplied by the integrator companies to represent birds at each KY site (proprietary information).

Actual bird population numbers were used in the PA data to reflect chick placement number on day 1 minus mortality and culls as the flock aged to account for the actual bird mass in the building for accurate emission calculations per unit bird mass. The KY data are presented in terms of initial bird placement numbers, which is the more common expression since it is cumbersome to track flock mortality in most regulatory situations. Other researchers have presented ER data based on placement numbers minus an assumed mortality (Seifert et al., 2004).

INSTRUMENTATION

Ammonia Measurement

Portable monitoring units (PMUs) were designed to monitor ammonia and carbon dioxide (CO₂) concentrations and static pressure difference between interior and exterior conditions. Detailed information about the design and performance of the PMU was provided by Xin et al. (2002), Xin et al. (2003), and Gates et al. (2005a). Briefly, the PMU was a tight-closing panel box that held instrumentation for emissions data collection and that was portable and cleanable for use in multiple houses. The PMU was wall-mounted near the monitored exhaust fan. At least one PMU was installed in each broiler house during a study period to monitor conditions of the exhaust air and fresh outside air. Instrumentation within the PMU included two identical gas monitors for redundant measurement of ammonia concentration (0-200 ±3 ppm, volume basis; PAC III, Dräger Safety, Inc, Pittsburgh, Pa.) with plumbing and controls (pump, solenoid valve, flow meters for controlled flow) for cycling fresh outside air and poultry house air past the sensors. The electrochemical sensors recorded gas concentration every 60 s and were purged with fresh air to reduce sensor saturation from continuous ammonia exposure. PA used a 30 min sample collection interval with 24 min of outside air and 6 min of poultry house air, while KY used a 20 min interval with the same house air exposure of 6 min but with 14 min of fresh purge air. (The longer purge time in the PA sensors was necessary to accommodate ammonia concentrations that exceeded 100 ppm during some cold-weather periods due to use of the PMU in a high-rise layer hen facility (data reported in Liang et al., 2005). A longer purge air time was beneficial for sensor recovery for continued accuracy in ammonia detection. Gas monitors read ammonia concentration every second and were set to record the time-averaged reading once per minute.

An ammonia value for emission rate calculation was selected from the 6 min interval of house air to represent ammonia level in the house over the house air / purge air cycle. The readings of both ammonia sensors were averaged for each minute, and the maximum average ammonia concentration was chosen for use in calculation. During PMU development, a comparison of NH₃ concentration recordings between a PMU and a chemiluminescence NH₃ analyzer (model 17C chemiluminescence NO-NO₂-NO_x analyzer, Thermo Environmental Instruments, Franklin, Mass.) was conducted *in situ* in a field emission laboratory that was installed next to a commercial laying hen house (Xin et al., 2003). The exhaust air NH₃ levels ranged from 6 to 45 ppm as recorded every minute by the chemiluminescence analyzer system, whereas the PMU used 12 min purging and 8 min sampling cycles and registered data every 30 s. Averages of the NH₃ readings by the chemiluminescence system during the PMU sampling cycles were calculated. These average values were compared with: (1) the maximum value of the PMU readings during the sampling cycles, (2) the difference between the maximum value of the sampling cycle and the minimum value of the purging cycle, or (3) the difference between the maximum value of the sampling cycle and the mean value of the last 2 min purging cycle. Paired t-tests were conducted between the chemiluminescence values and the PMU values, with results indicating that the maximum PMU value agreed well ($P = 0.33$) with the readings by the chemiluminescence emission laboratory setup, whereas the other comparisons were statistically different ($P = 0.0001$).

Ventilation Rate Parameters

Each PMU also monitored other parameters needed for ventilation rate determination. Static pressure difference (0-125 Pa, 0-0.5 in. H₂O; model 264, Setra Systems, Inc., Boxborough, Mass.) was recorded every minute and used in calculation of ventilation rate (described below). Carbon dioxide concentration (non-dispersive infrared sensor (0-5000 ±(20 ppm CO₂ + 2% of reading); model GMT222, Vaisala, Inc., Woburn, Mass.) was used as a fresh air indicator for purge air and as a second method of estimating ventilation rate (Li et al., 2004). Each electrochemical ammonia monitor had an internal datalogger that was temperature compensated. The other sensor outputs (solenoid switch of fresh-purge air, CO₂ sensor, sample gas temperature near the sensors, and static pressure difference) were recorded with a 4-channel, battery-operated data logger (4 to 20 mA ±0.1%, Onset Computer Corp., Bourne, Mass.).

INSTRUMENTATION POSITION

Ammonia and Carbon Dioxide

Two PMUs were typically installed in each house. One PMU, which was equipped with the building static pressure sensor, was located near and monitored the primary minimum ventilation fan. The second PMU was installed near a second minimum ventilation fan, if that fan was located in another chamber of the house. On some occasions, the primary minimum ventilation fan was in an unheated non-brood chamber of the house, and in other instances it was in the heated brood area. More commonly, the second PMU was located next to one of the larger tunnel fans to record emission variables when these fans were in operation and the sidewall fans were off. PMU placement depended on the farm manager's seasonal ventilation scheme during the 48 h study period.

Air samples were drawn into the PMU through two lengths of 6 mm (1/4 in.) i.d. transparent PVC tubing. The house air sample tube was 2 to 3 m long with the air intake positioned in front of the monitored exhaust fan (1/3 of the fan diameter down from the top, 15 cm horizontal offset from the fan center, 45 cm in front of the fan intake) and was equipped with a 20 µm paper filter (Whatman 41, No. 1441047, Middlesex, U.K.). The purge air intake was positioned outside the poultry house, at the eaves between fresh air inlet boxes on the house sidewall that did not have exhaust fans, and was equipped with an automotive-style pleated-paper air filter. Filters were used to prevent larger particulates and insects from clogging the air collection lines.

Static Pressure Difference

The differential static pressure sensor within the PMU had two ports for outside and inside pressure. The outside pressure was obtained via a length of PVC tubing that was run from the PMU to outside the poultry house, at the eaves between inlet boxes on the house sidewall where the PMU was hanging. At the eaves, the tube terminated inside a 2 L plastic bottle to minimize the effects from wind gusts on the recorded building static pressure. Interior static pressure was monitored from the second port on the PMU.

Temperature and Humidity

Indoor and outdoor temperature (T) and relative humidity (RH) were monitored with a combined temperature/relative humidity detector (±0.4 °C [±0.7 °F] and ±3% RH in

standard resolution mode over the temperature range under study; 1 min data recording interval; HOBO Pro Series, Onset Computer Corp., Bourne, Mass.) that was placed at approximately the house center about 60 cm above the litter surface (above bird reach). For monitoring outdoor conditions, PA used a T/RH detector (described above) outside under the building eave, protected from direct sunlight, and away from exhaust fans, while KY used a weather station located near the broiler houses, recording on a 6 min interval (temperature/RH accuracy = $\pm 0.7^\circ\text{C}$ at 25°C [$\pm 1.3^\circ\text{F}$ at 77°F] and $\pm 3\%$ RH; barometric pressure accuracy = ± 0.4 kPa [0.118 in. Hg]; HOBO Weather Station, Onset Computer Corp., Bourne, Mass.).

FAN VENTILATION RATE

Ventilation rate was calculated using actual fan performance and run-time data, and then corrected to conditions of standard temperature and pressure. Data recorded included static pressure difference of the ventilation system every minute. Fan run-time was recorded using on/off motor loggers (HOBO on/off motor, Onset Computer Corp., Bourne, Mass.) installed between the electric supply receptacle and plug to each fan. These loggers provided time of state change with a resolution of 0.5 s. Data were analyzed into 20 min (KY) or 30 min (PA) periods to match ammonia data analysis intervals.

To correct for standard atmospheric conditions, house temperature at bird level was averaged over the data collection interval. The temperature and site elevation (PA) and barometric pressure data from the weather station ((KY; described above) were used to correct all data to standard temperature (0°C) and pressure (101.325 kPa).

The “actual” exhaust fan ventilation capacity was determined *in situ* with a traversing anemometer array, the Fan Assessment Numeration System (FANS) unit (Gates et al., 2004; Casey et al., 2002). In short, the FANS consisted of five vane anemometers positioned on a bar that traversed the entire airflow entry area to each fan. The FANS was used to develop performance curves for each individual fan in each house (11, 14, or 15 fans per house) over a range of six typical building static pressure differences (0 to 50 Pa, 0 to 0.18 in. H₂O). The FANS was positioned on the intake side of the fan of interest and sealed against air leaks. Wheeler et al. (2002) provides additional detail of FANS use in field evaluations of fan ventilation capacity. All tests were done when the house had no birds present so that any ventilation condition could be evaluated without jeopardizing bird comfort.

It took about 1 h to fully evaluate each fan over the range of typical operating static pressure (SP) differences, so several trips to each farm were necessary to fully characterize each house’s ventilation system. In the cold-climate and farm KY-B houses, static pressure was monitored and controlled during the fan capacity trials via the house environmental controller’s static pressure instrument (Photohelic, Dwyer Instruments, Michigan City, Ind.), which was checked and zeroed (if necessary) before testing began. At farm KY-B, Photohelic calibrations were checked (PPC 500 portable pressure calibrator, Furness Controls, Ltd., Bexhill, U.K.) following testing and a correction applied to data as required. The SP setpoint needles on the Photohelic instrument were set to within about 1 mm of each other so that SP was kept in a narrow range by the inlet controller. Once the SP stabilized, a FANS traverse was run and recorded for KY houses, since

early testing revealed negligible difference between replicated runs. In PA, a second traverse was run right away. If the difference between the two runs was more than 3%, another pair of traverses was completed. This was done as a precaution, especially during conditions when wind pressures could affect fan airflow.

A similar, calibrated static pressure monitoring instrument (Magnehelic, Dwyer Instruments) was set up near the fan being evaluated by the FANS for additional validation of house static pressure. Fan ventilation rates were determined near the beginning of the study in PA. Additional tests of three to five fans in each house, performed near the end of the project, indicated no measurable difference in fan performance over the yearlong study period for these fans, which were cleaned between each flock.

At farm KY-A, there were computer controllers with integrated, electronic static pressure sensors, so the ventilation controller was turned off and the static pressure was set by manually opening vents while monitoring SP (Dwyer Series 475 Mk III handheld digital manometer, 0 to 1.00 in. H₂O). During each test, SP was continuously logged (Setra model 264 differential pressure transducer connected to a Hobo H08-006-04 4 channel logger sampling at 1 s intervals) with the average SP determined for each traverse period.

Under minimum ventilation for air quality during cold weather, the fan on-off times were known so that ventilation rate was constant over the 48 h evaluation time period. Timer fan on-off time was provided by the farm manager and verified with electronic controller settings, timed observation of the timer fan, and fan motor loggers.

Building ventilation rate was determined by multiplying fan capacity of each individual fan as determined from operating static pressure by that fan’s actual run-time during that data collection interval. All fans running during that 20 or 30 min interval were summed for the total building ventilation rate. Each interval was summed over a 24 h period. Reported ventilation data are the average rate in m³ h⁻¹ per 1000 birds for that 24 h period.

EMISSION RATE DETERMINATION

The NH₃ emission rate (ER) was calculated as the mass of NH₃ emitted from the broiler houses in a unit time. The ER (g h⁻¹ b⁻¹) was calculated using the following relationship:

$$\text{ER} = Q \times M \times ([\text{NH}_3]_e - [\text{NH}_3]_i) \times 10^{-6} \times \frac{w_m}{V_m} \times \frac{T_{std}}{T_a} \times \frac{P_a}{P_{std}} \quad (1)$$

where

- Q = building ventilation rate at interior temperature and site barometric pressure (m³ h⁻¹ kg⁻¹)
- M = average body weight of the birds (kg bird⁻¹)
- $[\text{NH}_3]_i$ = NH₃ concentration of building inlet air (ppm)
- $[\text{NH}_3]_e$ = NH₃ concentration of building exhaust air (ppm)
- w_m = molar weight of NH₃ (17.031 g mole⁻¹)
- V_m = molar volume of NH₃ at standard temperature (0°C) and pressure (101.325 kPa), or STP (0.022414 m³ mole⁻¹)
- T_{std} = standard temperature (273.15 K)
- T_a = absolute house temperature, (°C + 273.15) K
- P_{std} = standard barometric pressure (101.325 kPa)

P_a = atmospheric barometric pressure: KY weather station, PA site elevation (kPa)

NH_3 concentration of the exhaust air ($[\text{NH}_3]_e$) without subtraction of that from the intake ($[\text{NH}_3]_i$) was used in the calculation of emission rates for this study, as determined during a comparison with a chemiluminescence analyzer during PMU development (described earlier). In addition, background concentration of intake air was recorded during the fresh air purge cycle and was found to contain 0 NH_3 on almost all occasions. For example, with birds less than one week old during cold weather conditions, ammonia was 5 to 7 ppm inside and 0 ppm outside at farm PA-A and 30 to 40 ppm NH_3 inside at farm PA-B with 0 ppm NH_3 outside most of the time. In the latter case, near the end of the 48 h monitoring period, occasionally the purge air recorded 0 NH_3 and then climbed to 1 or 2 ppm NH_3 near the end of the fresh air purge cycle. During the fifth week of these flocks, the interior ammonia at farm PA-A was 24 to 27 ppm with outside purge air at 0 ppm, while at farm PA-B the interior was 60 to 80 ppm with outside purge air 0 ppm NH_3 during the entire monitoring period. Therefore, it seemed satisfactory to disregard the outside, purge air ammonia level.

DATA INTEGRITY

All ammonia sensors were calibrated immediately prior to each study field trip (procedure below) and checked for calibration upon return from the field. Obtaining accurate ammonia calibration gas remains a challenge and should be part of quality assurance methods of the project protocols. Electrochemical sensors have a limited life, and replacement cost was included in the original project cost. Any sensors that did not pass the post-field check were further evaluated and replaced if necessary from spare sensor inventory. All sensors heads in PA were replaced halfway through the 16 months of use (this included startup months and additional months in layer hen facilities in addition to the 12 months in broiler houses) in an attempt to maintain sensor integrity. In KY, a particular sensor was replaced when it was identified as defective or had been used for sixty 24 h monitoring periods (determined from expected sensor life and exposure).

Calibration gases used in PA were certified during October 2002 with values of 18.6, 47.9, and 103 ppm ammonia (balance nitrogen; Master Standard Mixture, Messer MG Industries, Morrisville, Pa.). The gases were recertified during October 2003 for an additional year with values of 18.9, 48.3, and 104 ppm. A two-point calibration was performed for each 48 h monitoring interval with span dependent upon anticipated ammonia concentration at the study sites using zero ammonia as nitrogen gas and nominal 20, 50, or 100 ppm ammonia gas.

A single cylinder of 49.5 ppm ammonia calibration gas was used in KY during the course of the project (CEM-2 Daily Standard, Scott Specialty Gases, Plumsteadville, Pa.). Following the conclusion of the project, a new cylinder of 54 ppm ammonia calibration gas was purchased from the same supplier. It was noticed that the certified analyses of the two cylinders were inconsistent during periodic checking with a highly accurate ammonia instrument (model 1314 photoacoustic multi-gas monitor, Innova, Denmark). Both cylinders were returned to the manufacturer, where their contents were reanalyzed in replicate. The original certification was in error, and the original cylinder was recertified at

62.3 ppm and the newer cylinder at 54.1 ppm. Based on this recertification, a linear correction (62.3/49.5) was applied to all recorded ammonia concentrations.

Raw data from KY were shared with PA, and vice versa, to check for errors and omissions in calculations. Uniform parameters were agreed upon, as were protocols for grooming the data from raw values to final emissions numbers. Even though the two research stations proceeded through the emissions calculation (eq. 1) slightly differently during spreadsheet development, the end result was virtually identical when the same data were cross-checked using the two different methods during the quality control evaluation.

RESULTS

AMMONIA CONCENTRATION AND VENTILATION RATE PER FLOCK

Figures 1 through 4 provide individual flock ammonia concentrations, ventilation rates (VR), and emission rates (ER) from each of the four sites, expressed as daily averages for each house and for each 24 h study period. The seasonality and correlation of ammonia concentration and ventilation rate become apparent with lower ammonia concentration and higher VR during warm summer conditions, while ammonia concentration tended to be higher during cold weather when low ventilation rates provided less fresh air dilution of ammonia. Ammonia concentration, measured at the building exhaust, increased with flock age in all cold-climate houses (figs. 1a and 2a), especially in the six flocks that started on new litter (all five flocks at farm PA-A and the second flock at farm PA-B) where initial ammonia level was very low (<10 ppm). Higher ammonia levels recorded later in each flock cycle were not anticipated for the used-litter houses (farm PA-B) since increased warm weather ventilation rates should have diluted building ammonia concentration. Interestingly, VR of the cold-climate built-up litter houses did not increase substantially as the flock aged until late summer and fall. But note that flock 3 during May was only monitored twice, when birds were 3-4 and 20-21 days old, where high VR would not be expected. The mixed-humid climate exhaust ammonia concentration (figs. 3a and 4a) followed an increasing pattern with bird age for those flocks under winter conditions (Oct. to Feb.) but was steady or decreasing during the spring, summer, and fall conditions when increasing ventilation rates were used later in the flock cycle (figure 3b and 4b). The results shown in figures 1a through 4a and 1b through 4b are the foundation data from which the emission rates were calculated.

EMISSION RATE PER FLOCK

Individual flock emission rates are shown in figures 1c through 4c for each site, and provide evidence that ER at a given bird age can be relatively uniform from flock to flock throughout the seasons despite the large variations in seasonal house exhaust ammonia concentration and ventilation rates. The highest ER was measured during the warmest weather, especially in the mixed-humid climate houses, where very high VR were used to provide convective cooling of birds during hot weather (tunnel ventilation) with VR exceeding that needed for simple heat removal.

Regression equations for each flock ER are offered in terms of $\text{g NH}_3 \text{ bird}^{-1} \text{ d}^{-1}$ versus flock age in days. The

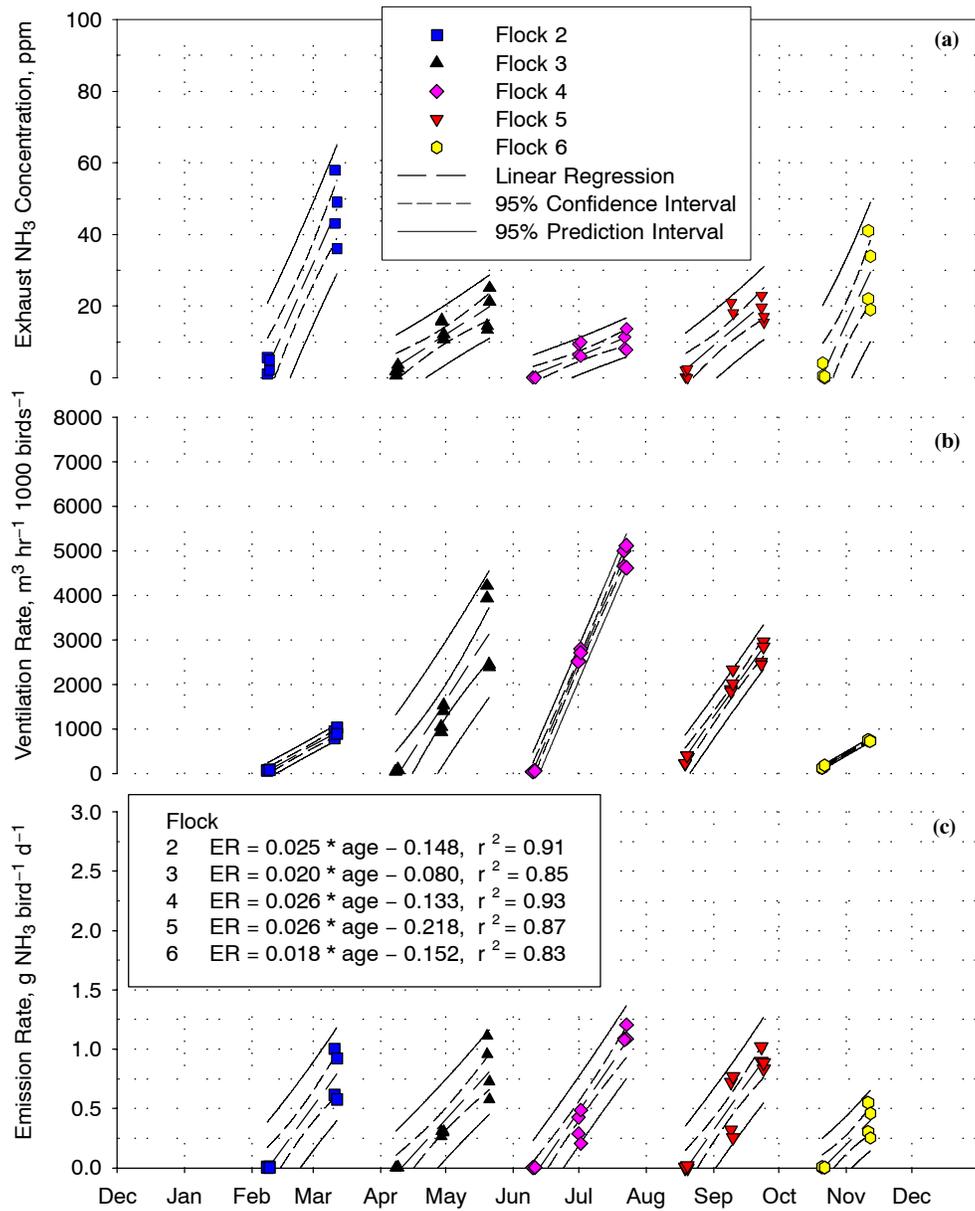


Figure 1. Individual flock presentation versus date for farm PA-A managed with new litter every flock: (a) average daily ammonia concentration, (b) ventilation rate for each flock cycle over the one-year study period, and (c) average emission rate per bird per day of age, with individual flock regression equations.

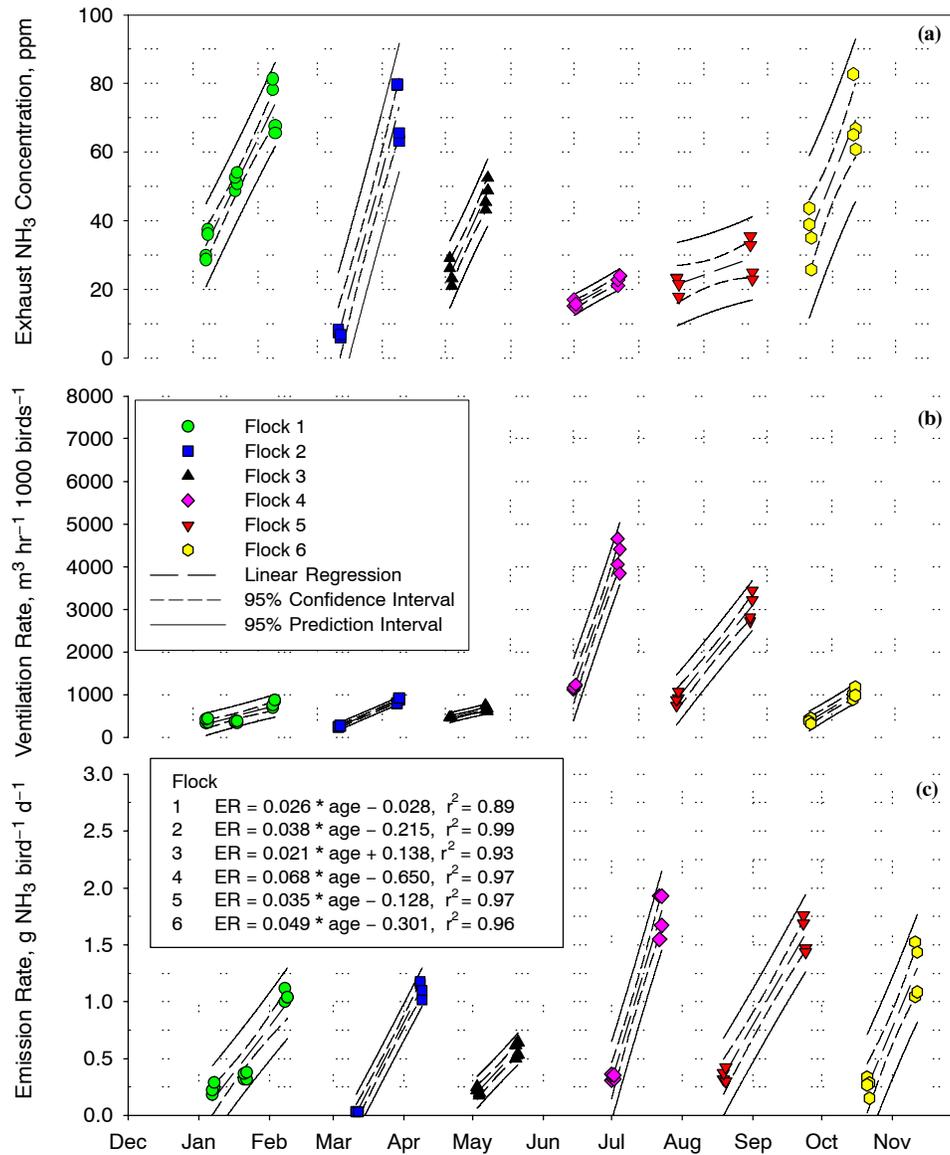


Figure 2. Individual flock presentation versus date for farm PA-B managed with built-up litter, except flock 2 on new litter: (a) average daily ammonia concentration, (b) ventilation rate for each flock cycle over the one-year study period, and (c) average emission rate per bird per day of age, with individual flock regression equations.

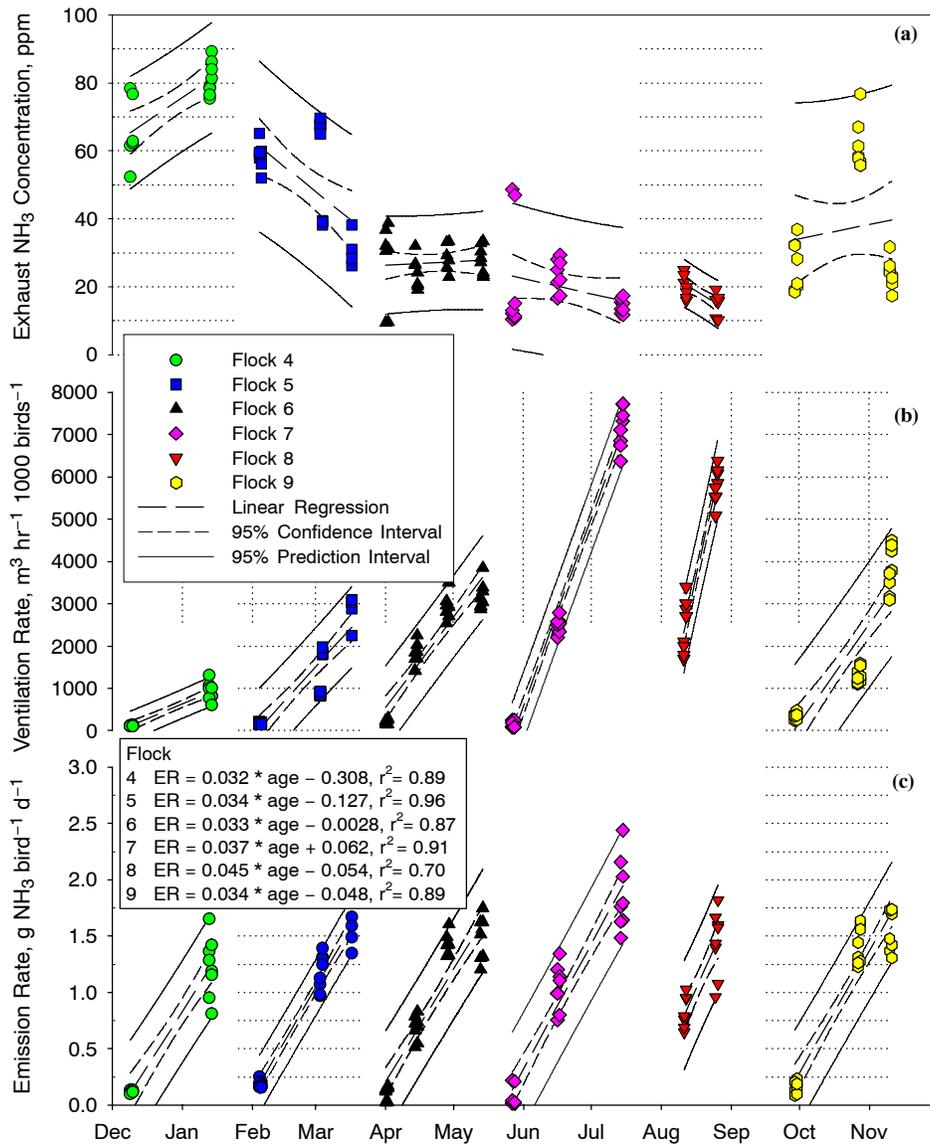


Figure 3. Individual flock presentation versus date for farm KY-A managed with built-up litter, except flock 7 on new litter (in three of four houses): (a) average daily ammonia concentration, (b) ventilation rate for each flock cycle over the one-year study period, and (c) average emission rate per bird per day of age, with individual flock regression equations.

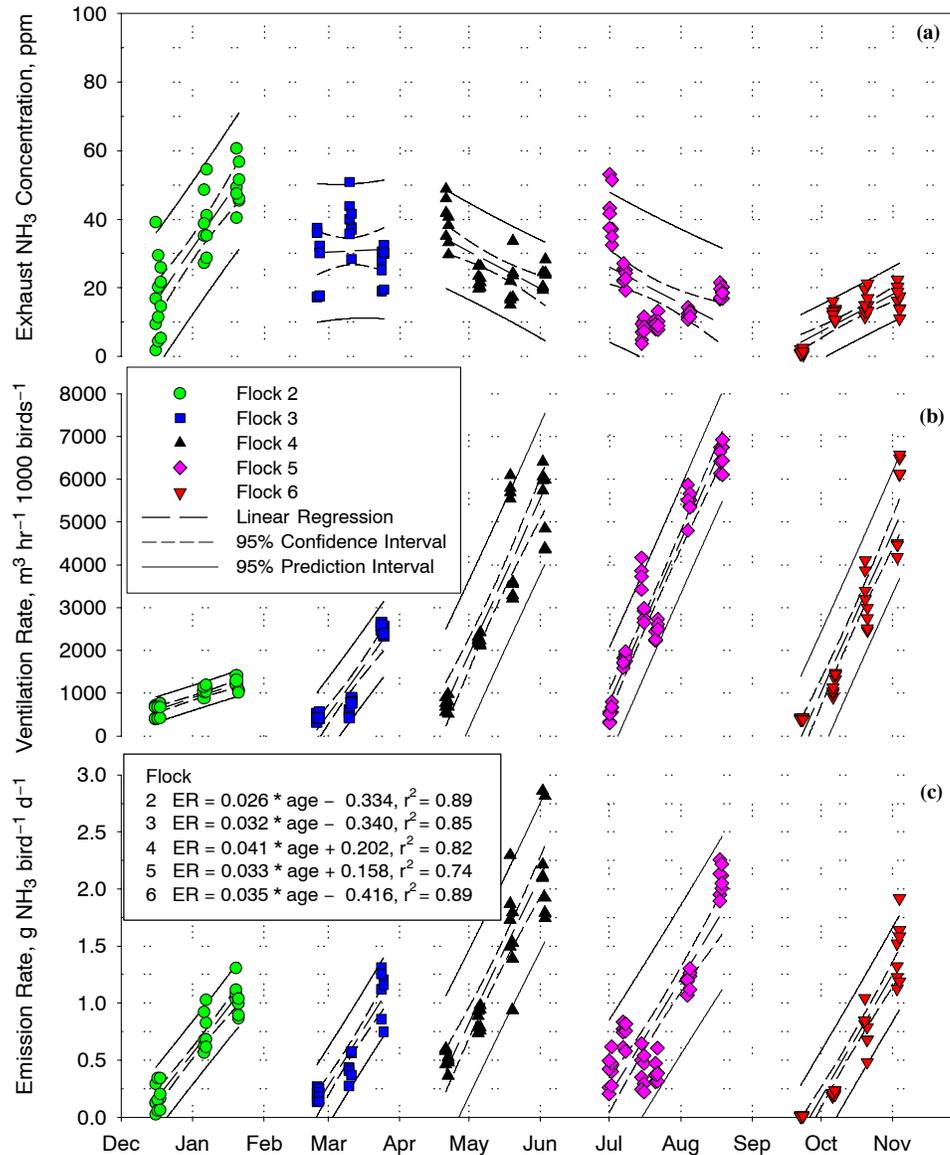


Figure 4. Individual flock presentation versus date for farm KY-B managed on built-up litter, except flock 6 on new litter: (a) average daily ammonia concentration, (b) ventilation rate for each flock cycle over the one-year study period, and (c) average emission rate per bird per day of age, with individual flock regression equations.

variability in regression slopes can indicate the range of daily emission encountered among these flocks. For flocks with at least three monitoring periods (13 flocks among all four sites), daily emission averaged $0.031 \text{ g NH}_3 \text{ bird}^{-1} \text{ d}^{-1}$ per day of age (range = 0.020 to 0.041; std. dev. of slope = 0.0057). In contrast, flocks for which only two monitoring periods were performed (9 flocks among all four sites, with 5 of those at farm PA-B) offered more variable results with a similar ER slope mean of $0.037 \text{ g NH}_3 \text{ bird}^{-1} \text{ d}^{-1}$ per day of age but with a larger range and variability (0.018 to 0.068; std. dev. = 0.0155). Farm PA-B had the most variable flock regression slopes, averaging $0.040 \text{ g NH}_3 \text{ bird}^{-1} \text{ d}^{-1}$ per day of age with a range of 0.021 to 0.068. There would appear to be benefit in monitoring a flock for at least three study periods spread out over the full time period of the flock to obtain a reasonable emission estimate that represents the flock cycle. Intercepts for these regression lines showed more vari-

ability than slope and were analyzed as part of the composite of all data from each flock.

The data also indicate the potential for wide variation in daily ER from identical houses. This variation is particularly apparent with KY-A and KY-B data, where four side-by-side houses were monitored at each site. There was often as much or more variation in ER among the identical houses as there was from one day to the next. This provides evidence for monitoring multiple facilities, when economically and logistically possible, to capture the naturally occurring variation in typical emission rates.

EMISSION RATE PER ANIMAL UNIT

Figures 5 through 8 show ammonia emission results versus bird age as composites of all study dates at each of the four farms. An evaluation of daily ER in terms of 500 kg animal unit ($\text{g NH}_3 \text{ AU}^{-1} \text{ d}^{-1}$) is shown in figures 5a through

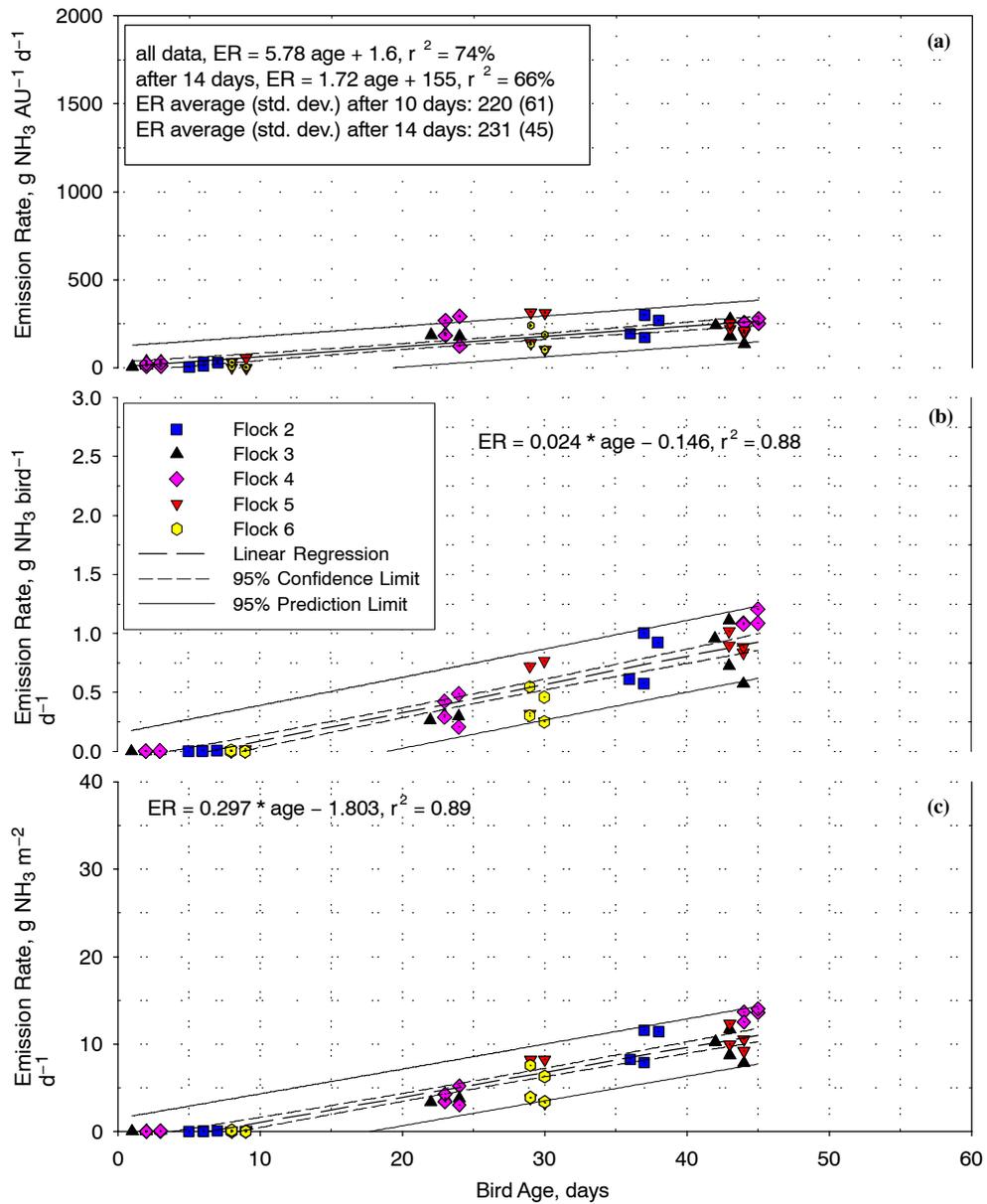


Figure 5. Composite of all flocks' emission rate for farm PA-A. Daily average emission rate expressed (a) per 500 kg AU, (b) per bird, and (c) per floor area for all study flocks.

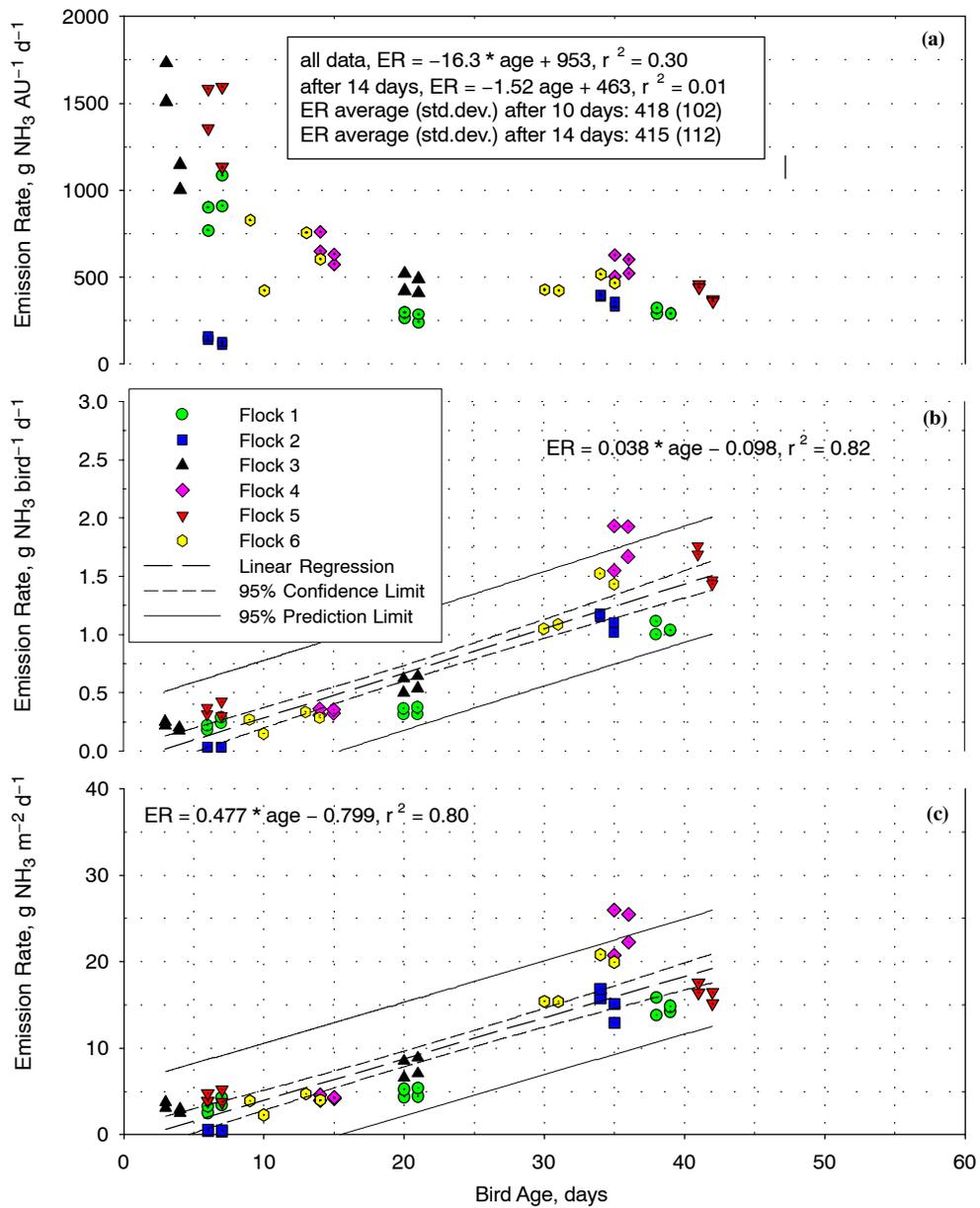


Figure 6. Composite of all flocks' ER for farm PA-B. Daily average emission rate expressed (a) per 500 kg AU, (b) per bird, and (c) per floor area for all study flocks.

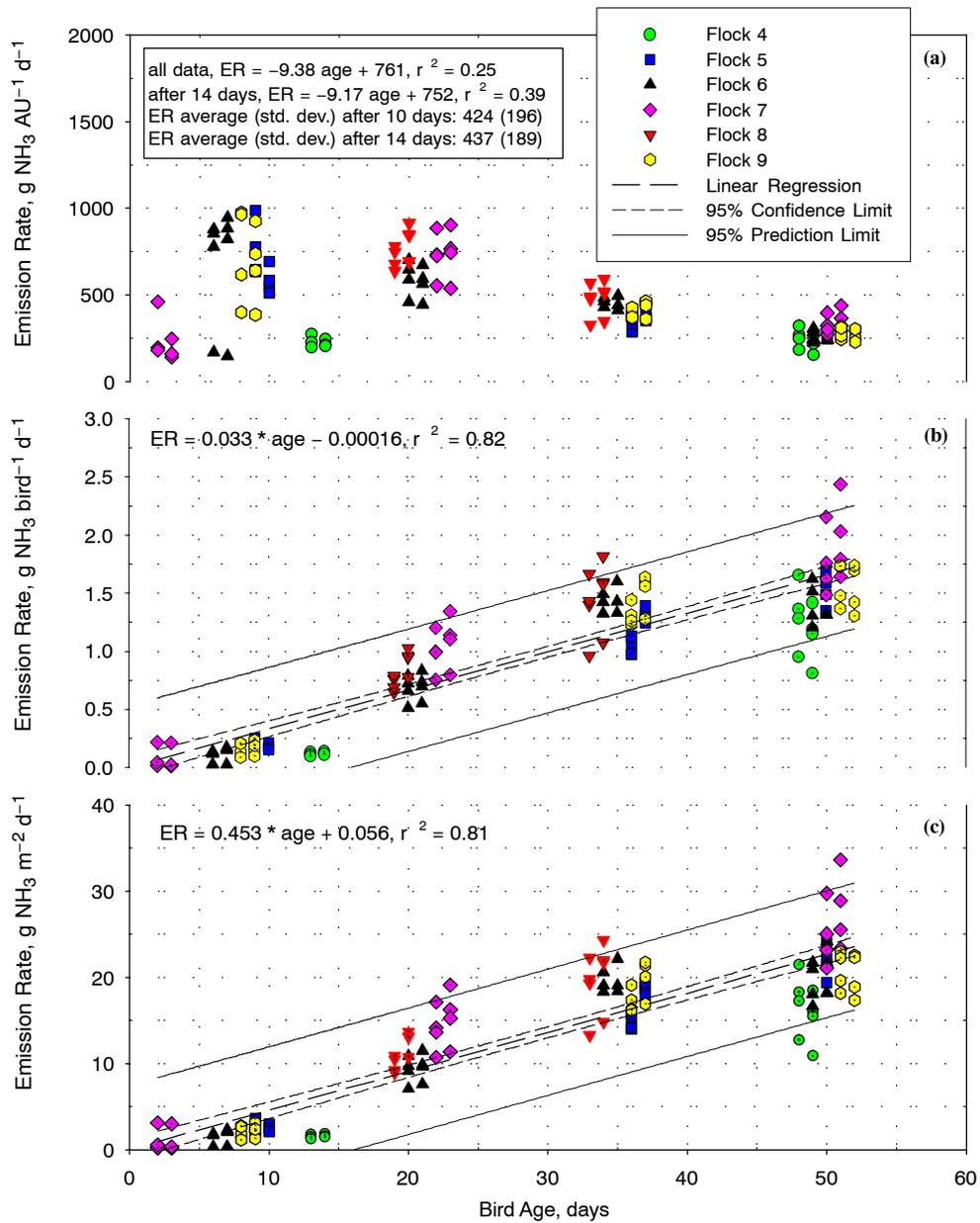


Figure 7. Composite of all flocks' ER for farm KY-A. Daily average emission rate expressed (a) per 500 kg AU, (b) per bird, and (c) per floor area for all study flocks.

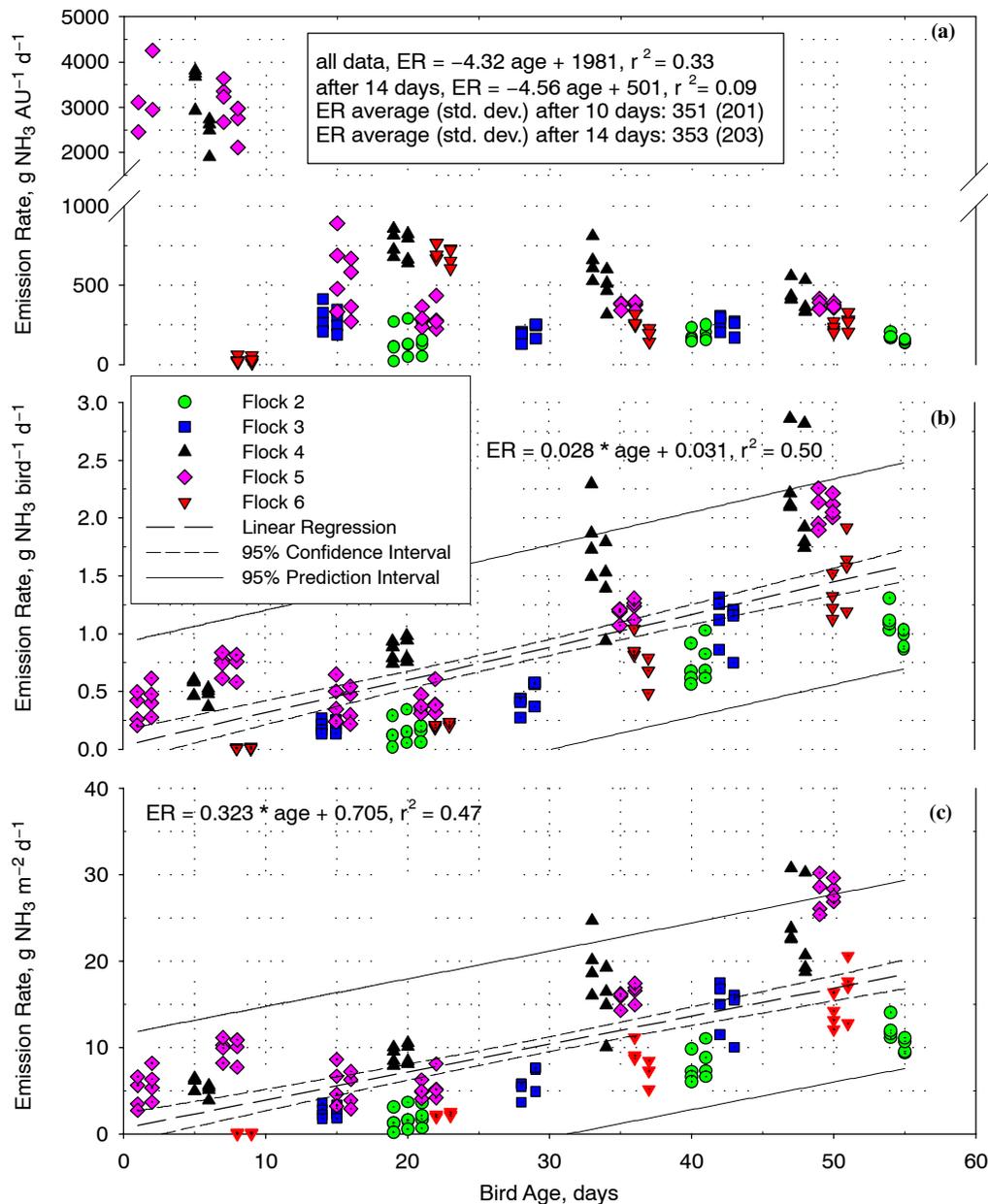


Figure 8. Composite of all flocks' ER for farm KY-B. Daily average emission rate expressed (a) per 500 kg AU, (b) per bird, and (c) per floor area for all study flocks.

8a. For the cold-climate houses, ER ($\text{g NH}_3 \text{ AU}^{-1} \text{ d}^{-1}$) for farm PA-A using new litter for each flock increased with increasing bird age (fig. 5a), while at farm PA-B on built-up litter the opposite occurred; ER per AU decreased with advancing bird age (fig. 6a). Further evidence for the strength of these trends is shown in figure 6a, where the increasing trend in ER $\text{g NH}_3 \text{ AU}^{-1} \text{ d}^{-1}$ with bird age on new litter is seen in flock 2, which started on new litter, while the other flocks were started on built-up litter. Farm KY-A also showed an influence of age, after 14 days, on decreasing ER per AU (fig. 7a). Results from houses in both climates studied indicated that there was generally no strong trend of bird age on ER per AU when birds were older than about 14 days of age. Farm KY-B houses had very high ER per AU early in the flock cycle, after which time the trend settled into a pattern

that did not vary with flock age (fig. 8a). Other than at farm KY-A, after 14 days of age the regression relationship of ER expressed as $\text{g NH}_3 \text{ AU}^{-1} \text{ d}^{-1}$ versus bird age was below 0.10 on built-up litter.

An estimate of daily NH_3 emissions per animal unit (\pm std. dev.) from these data is:

On built-up litter after 14 days bird age:

$$\text{ER}_{\text{AU}} = 400 \pm 200 \quad (2)$$

On new litter after 14 days bird age:

$$\text{ER}_{\text{AU}} = 225 \pm 50 \quad (3)$$

where ER_{AU} = emissions rate ($\text{g NH}_3 \text{ AU}^{-1} \text{ d}^{-1}$).

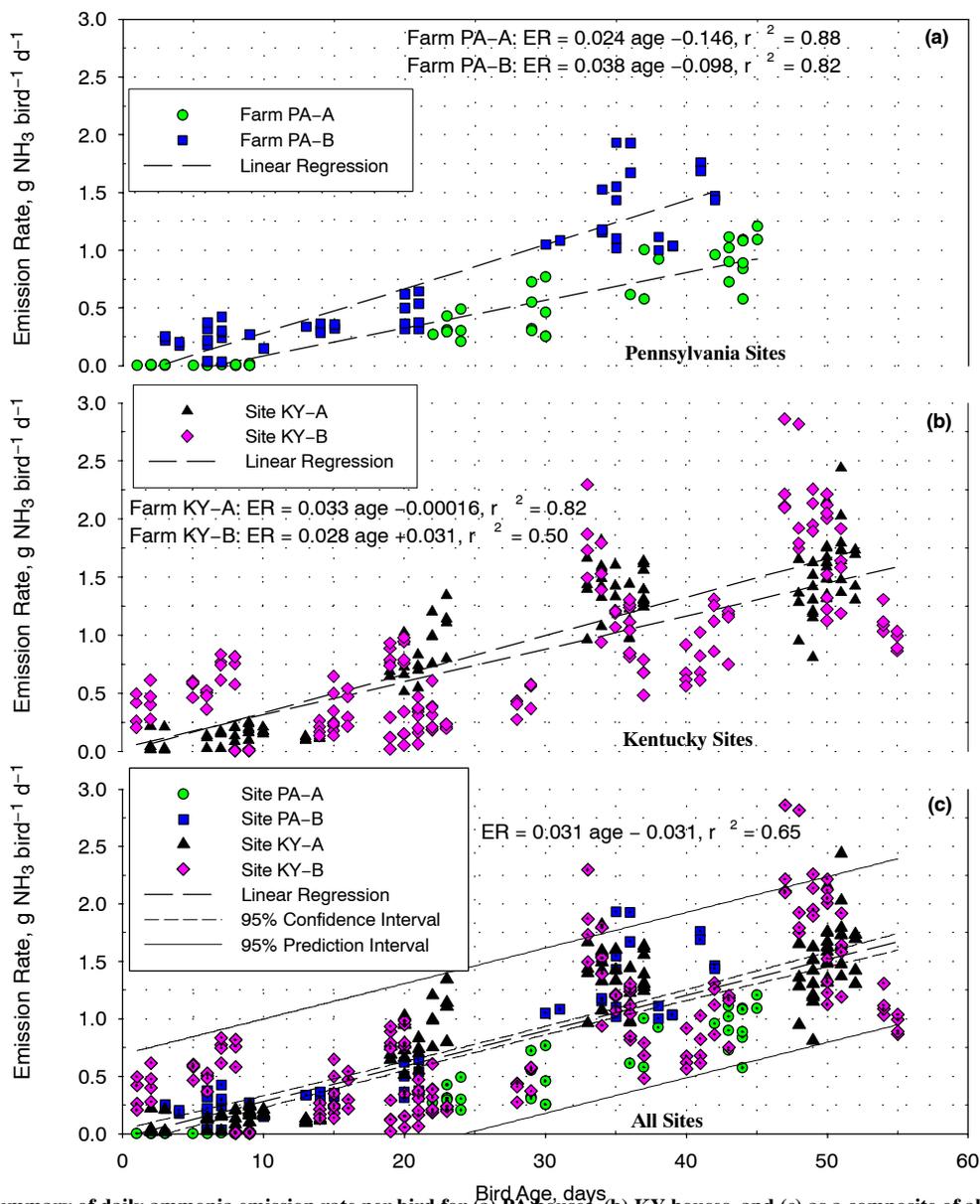


Figure 9. Summary of daily ammonia emission rate per bird for (a) PA houses, (b) KY houses, and (c) as a composite of all data together.

DAILY EMISSION RATE PER BIRD VERSUS FLOCK AGE

Daily ER values are expressed as g NH₃ bird⁻¹ d⁻¹ versus bird age (days) in figures 5b through 8b. Bird age during monitoring for each flock may be determined from figures 5 through 8. Coefficient of determination (r^2) values for ER regressed versus age from three of the four farms was the highest (above 0.82) among data relationships presented. Regression slopes of all collected daily ER versus age for each study site were 0.028, 0.033, and 0.038 g NH₃ bird⁻¹ d⁻¹ per day of age for built-up litter flocks and 0.024 g NH₃ bird⁻¹ d⁻¹ per day of age for new litter flocks at farm PA-A. For sites with built-up litter, the intercept was virtually 0 (farm KY-A), equivalent to 1.0 day ER (farm KY-B), and equivalent to 2.6 days for farm PA-B. In contrast, new-litter farm PA-A had an intercept equivalent to 6 day ER. These intercept equivalents are of interest when evaluating flocks during early days in the cycle. For farm KY-B, the intercept equivalent of 1 day represents less than 2% emission of this 55-day flock cycle. For these built-up litter houses, the intercept may be ignored and emissions

estimated with slope alone of 0.028 to 0.038 g NH₃ bird⁻¹ d⁻¹. At placement of birds, considered one day old, there will be ammonia emission on built-up litter. Further analysis of our data may reveal conditions where the higher or lower ER slope estimates should be used. For the new-litter houses, the regression intercept is an important component of the emissions estimation and essentially reflects zero emission during the first six days of the flock cycle (since negative emission is not possible) when little manure accumulates under the chicks and low VR were used. This 6-day period with virtually no emission not only reduces the total house emission over the 45-day flock cycle at these study houses at the beginning of the flock, but also reduces overall emission by about 6 d × 0.031 g NH₃ bird⁻¹ d⁻¹, or about 0.2 g NH₃ bird⁻¹. Farm PA-B also had a significant negative intercept equivalent to about 2.6 days of emissions. The manager at this farm manager reduced ventilation during cold weather conditions and into warmer weather, which may have influenced early flock emissions.

DAILY AMMONIA EMISSION RATE ESTIMATE

An estimate of daily NH₃ emissions per bird (\pm std. error) from all data from all four farms, as shown in figure 9c, is thus:

$$ER_b = 0.031 (\pm 0.0011) \cdot age \quad (4)$$

where

ER_b = emissions rate (g NH₃ bird⁻¹ d⁻¹)

age = flock age (d) if built-up litter is used:

age = 0 d if new litter and flock age is <7 d;

age = (flock age - 6) d if new litter and flock age is \geq 7 d.

Table 4 provides comparison of ammonia emission rates measured during field trials in commercial broiler houses in the U.S. and Europe during the past 15 years. All study data are expressed in terms of ammonia emission per bird per day, which usually required conversion of the originally reported results based on information provided (or inferred) from the research article. One of the challenges in understanding and reporting emission data is the wide variation in reporting units that are not always inter-convertible depending on the

supporting information provided in the article. Annual data was problematic for conversion of broiler emission data since buildings are unoccupied during cleanout between flocks, with reduced (typical) emissions due to cooler interior temperatures, no additional manure deposition, opportunity to reduce litter moisture content with no further moisture addition, and eventually spent litter removal (for houses using new litter each flock), which eliminates the ammonia source. The report for annual emission factors should indicate the number of days in a year, since it may range from about 250 to 290 days when based on bird occupancy, instead of 365. In conversions of data (table 4) that were originally expressed in terms of 500 kg animal unit (livestock unit), average bird weight during a flock grow-out was estimated as one-half the finished market weight. Although this may underestimate average broiler weight due to rapidly increasing growth rate after about two weeks of age, it is the simplest available means when detailed growth curves are not provided with the data. The techniques and challenges of estimating annual emissions from broiler facilities are included in Gates et al. (2005b).

Table 4. Summary of ammonia emission rates from broiler houses as determined via actual measurements (rather than mass balance) expressed in terms of flock average emission while birds occupied the house. Where necessary, data were converted from original units to common expression using average bird mass.

Reference and Study Location	Flock Characteristics				Emission Rate (g NH ₃ b ⁻¹ d ⁻¹)	Monitoring				
	Market Age ^[a] (days)	Final Weight (kg)	Stocking Density (b m ⁻²)	Litter ^[b]		Number of:		Periods	Duration	Method ^[d]
Wheeler (this study), U.S. (Pennsylvania and Kentucky)	42 (1-45)	2.2	14.7	N	0.47	2 (5 each)	All	13	48 h	C-EC
	42 (2-42)	2.2	14.7	B, T	0.65	2 (6 each)	All	13	48 h	C-EC
	49 (1-53)	2.5	13.4	B, T	0.76	4 (6 each)	All	17	48 h	C-EC
	63 (1-55)	3.3	10.8	B, T	0.98	4 (5 each)	All	20	48 h	C-EC
Seifert et al (2004), U.S. (Delaware)	42 (29-37)	n/a	20.0	B?	1.18	1 (1)	Sp, Su	7	6-12 h	S-CM ^[e]
Müller et al (2003), Germany and Czech Rep.	32 (13-30)	1.6	n/a	N?	0.09	2 (1)	W	5	1 h	C-PS?
Lacey et al (2003), U.S. (Texas)	49 (8-47)	2.4	13.5	B	0.63	4 (3 each)	Su, F	10	3 S/d	S-CM
Burns et al (2003), U.S. (Tennessee)	42 (1-42)	2.3	16.1	B	0.92	1 (9)	All	9	42 d	C-EC
Demmers et al. (1999), United Kingdom	32 (1-32)	1.9	25	N	0.11	1 (1)	Su	1	32 d	C-CL
Wathes et al (1997), United Kingdom	32 (24-35)	1.1W 1.4 Su	9.3 W 9.4 Su	N?	0.26	4	Su, W	2	24 h	C-CL
Groot Koerkamp et al (1998)										
United Kingdom	-- ^[f]	--	--	N?	0.48	4	Su, W	2	24 h	C-CL
The Netherlands	--	--	--	N?	0.27	4	Su, W	2	24 h	C-CL
Denmark	--	--	--	N?	0.21	4	Su, W	2	24 h	C-CL
Germany	--	--	--	N?	0.44	4	Su, W	2	24 h	C-CL

[a] Age during measurement shown in parentheses.

[b] Litter: N = new, B = built-up, and T = treated.

[c] Season: Sp = spring, Su = summer, F = fall; W = winter, and All = all seasons.

[d] Monitoring method: C = continuous, S = sample, discrete, EC = electrochemical extraction, PS = photoacoustic extraction, CL = chemiluminescence extraction, and CM = colorimetric tube.

[e] Downwind passive samplers and Gaussian plume model back-calculation of emission at building.

[f] Flock characteristics not provided, so data not converted to average bird weight basis.

? = Not explicitly stated but inferred from data, statements in article, or common practice.

n/a = Not available.

The cost and complexity of field measurements of emissions resulted in most studies reported in table 4 having a limited but useful database of information. The study reported here, with twelve houses each monitored intermittently over all flocks placed during a year of production with four-hundred 24 h days of information, is the most comprehensive database to date.

The average emission rate over a flock cycle increases when birds are raised to greater weights, on built-up litter, and/or at high stocking densities. Ammonia ER of U.S. broilers raised under typical commercial conditions to 42 days on built-up litter were fairly consistent among studies, ranging from 0.63 (Lacey et al., 2003) and 0.65 g NH₃ b⁻¹ d⁻¹ (this study) to 0.92 g NH₃ b⁻¹ d⁻¹ (Burns et al., 2003) and 1.18 g NH₃ b⁻¹ d⁻¹ (Seifert et al., 2004). Broiler stocking densities for a finished bird weight of about 2.2 to 2.4 kg in these studies ranged from 14.7 to 20.0 b m⁻², with higher ER values corresponding to increased stocking density. Increasing bird density has the potential for higher ammonia emissions due to its associated increased uric acid (precursor to ammonia) excretion per floor area. Broilers raised under similar conditions in the U.S., but on new litter each flock, had a reduced ER of about 0.47 g NH₃ b⁻¹ d⁻¹. Similarly, European birds are typically raised on new litter each flock, resulting in a reduced ER (Groot Koerkamp et al., 1998). In addition, the lighter bird weight produced for the European market provided further ER reduction. Two studies demonstrated ER around 0.1 g NH₃ b⁻¹ d⁻¹ for birds grown to 1.6 or 1.9 kg (Muller et al., 2003, and Demmers et al., 1999, respectively).

The ammonia emission rate data presented here has been represented by linear relationships, with slope and intercept used to differentiate between farm sites or manure management. Other literature represented ER over the flock cycle by a second-order polynomial relationship (Muller et al., 2003; Demmers et al., 1999), similar to the broiler growth curve in shape, that better acknowledges the minimal emissions on new litter and the dramatic emission increase during the second half of broiler flock growth.

FLOOR AREA-BASED EMISSIONS

Ammonia emissions originate from the manure deposited on the litter of the broiler house floor. Another way of expressing emission is in terms of the emitting surface, or floor area. Figures 5c through 8c indicate that floor-based expression of emission rate per unit area is very similar in pattern to that expressed on a per bird basis versus flock age, with a similar r².

SUMMARY

Figure 9 presents summary information for daily emission rates found from the four farm sites under study in the two U.S. climates. Using equation 4 for daily ammonia ER per bird will provide a good estimate based on the most comprehensive database of emissions from a variety of broiler chicken facilities collected to date. The relationship is useful for birds aged 1 to 63 days that are managed on built-up or new litter. A relationship for daily ammonia ER expressed in terms of animal unit is provided in equations 2 and 3 for built-up and new litter flocks, respectively, but the large variation will limit their usefulness.

CONCLUSIONS

The information presented here provides 400 data-days of ammonia emissions from current practices in commercial broiler houses and represent a significant advancement in characterizing baseline ammonia emissions from U.S. broiler facilities. There was little difference in ammonia emissions generated within the two study climates, cold and mixed-humid. There were seasonal trends in exhaust ammonia concentration, with generally higher values during cold weather periods corresponding to relatively low ventilation rates. In contrast, the higher ventilation rates used during warmer seasons and with older birds generally resulted in lower house ammonia levels. These offsetting relationships resulted in fairly uniform ammonia emission rates from flocks of same-age birds over the seasons, but with slightly higher emission rate observed during the hottest weather.

The best predictive relationship using all data was found between average daily emission rate per bird and flock age: ER (g NH₃ d⁻¹ bird⁻¹) = 0.031 × *age* (std. error = 0.0011), where *age* is actual bird age (in days) for birds on built-up litter and (*age* - 6) for birds on new litter (ER = 0 from new litter flocks less than 7 days old). Another good relationship was found between emission rate per floor area versus flock age, which acknowledges the floor, rather than the birds, as the ammonia emission source.

Emission rate in terms of animal unit was usually independent of bird age after about 10 to 14 days of age. The relationship for built-up litter flocks indicated very high emissions per AU for the youngest birds (under about 14 days of age), after which time the emissions were lower and relatively steady for the balance of the flock cycle: ER_{AU} (g NH₃ AU⁻¹ d⁻¹) = 400 ± 200. For new litter houses, the emission rate per AU was very low for the youngest birds and then higher and steady after 14 days of age: ER_{AU} (g NH₃ AU⁻¹ d⁻¹) = 225 ± 50.

Flocks that had at least three monitoring periods (13 of the 22 flocks in this study) provided emission rates that were similar among the four study farms and across the seasons (regression slope average = 0.031 g NH₃ bird⁻¹ d⁻¹ per day of age; std. dev. = 0.0057). Flocks with only two monitoring periods (9 flocks) had less uniformity among the predictive emission relationships (regression slope average = 0.037 g NH₃ bird⁻¹ d⁻¹ per day of age; std. dev. = 0.0155). It is recommended that at least three monitoring periods be used during a flock cycle to better determine emission trends.

When all flock data from each farm were analyzed as a composite, the three farms with built-up litter had predicted regression slopes of 0.028, 0.033, and 0.038 g NH₃ bird⁻¹ d⁻¹ per day of flock age. For the fourth farm, using new litter for each flock, the slope was the lowest at 0.024 g NH₃ bird⁻¹ d⁻¹ per day of flock age. The intercept of these composite linear relationships was influenced by litter conditions, with flocks on new litter having essentially no emissions for about six days and built-up litter flocks having an intercept near zero. Hence, emissions can be estimated as a simple function of bird age for these houses. Further analysis is needed that includes evaluation of all new litter flocks, regardless of study site, and evaluation of litter treatment effect on emissions.

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